Quantum effects in thermal Fock state for mesoscopic left-handed transmission lines*

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A quantization scheme for an ideal loss-less mesoscopic left-handed transmission lines (LH TL) unit cell equivalent circuit is proposed and the fluctuations of the current and the voltage of the LH TL equivalent circuit in thermal Fock space are studied by thermal field dynamics (TFD) theory. In thermal Fock state the negative refractive index (NRI) of the LH TL unit cell equivalent circuit is discussed. The results indicate that the quantum fluctuations show the linear dependent of NRI at some temperature, while the frequency and the thermal photons are destructive dependent of NRI within the microwave frequency band. When the unit cell equivalent circuit operates at the rising temperature, the NRI is decreasing. The results demonstrates the ideal loss-less mesoscopic LH TL equivalent circuit operating at a lower frequency, temperature and with little thermal photons is more conducive to NRI, which coincides with the macroscopic real LH TL.

I. INTRODUCTION

The theoretical speculation of negative refractive index materials (NRM) proposed by V. Veselago[1] in 1968, in which several fundamental phenomena occurring in or in association with NRM were predicted, such as the negative Goos-Hänchen shift[2], amplification of evanescent waves[3], reversals of both Doppler shift and Cerenkov radiation[1], sub-wavelength focusing[4] and so on. Some typical approaches can be summarized as artificial structures such as metamaterials[5–7] and photonic crystals[8–10], chiral materials[11] and photonic resonant media[12, 13]. Although very exciting from a physics point of view, the artificial structures seem of little practical interest for engineering applications because of these resonant structures exhibiting high loss and narrow bandwidth consequently. Due to the weaknesses of resonant-type structures, three groups almost simultaneously in June 2002 introduced a transmission line (TL) approach of NRM: Eleftheriades et. al[14, 15], Oliner[16] and Caloz et. al.[17, 18]. LH TL initially the nonresonant-type one, is perhaps one of the most representative and potential candidates due to its low loss, broad operating frequency band, as well as planar configuration[19, 20], which is often related with easy fabrication for negative refractive index (NRI) applications in a suite of novel guided-wave[21], radiated-wave[22], and refracted-wave devices and structures[23, 24].

However, with the rapid development of nanotechnology and nanoelectronics [25], the integrated circuits and components have minimized towards atomic-scale dimensions[26, 27] in the last a few decades. When the scale of fabricated electric materials reached to a characteristic dimension, namely, Fermi wavelength, quantum mechanical properties of mesoscopic physics[28, 29] become important while the application of classical mechanics fails. The miniaturization of applications would be undoubtedly a persistent trend for LH TL, and quantum properties maybe its future challenge. So it's significance to investigate the quantum properties before the applications of LH TL approaching to nanometer scale.

Thus, from the point of against this challenge, this paper exploits the dependence of quantum properties of thermal noise, the quantum fluctuations of current and the frequency of LH TL on NRI. In Section 2 , we quantize the non-time-dependent Hamiltonian for the ideal non-dissipative LH TL equivalent circuit via the analogy with harmonic oscillator. In Section 3, we derive the NRI for this LH TL circuit via the quantum fluctuations of

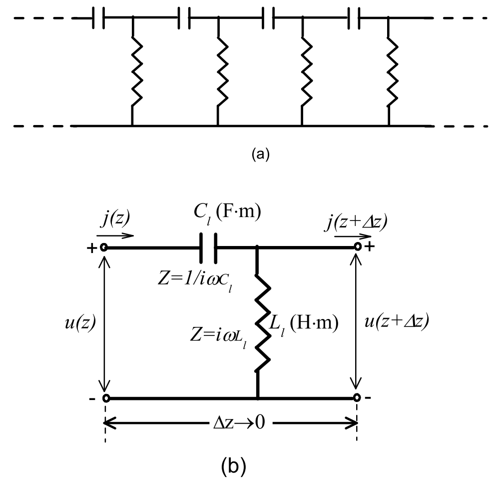

FIG. 1. (a)Equivalent circuit model for the hypothetical uniform Left-handed Transmission Line,(b)Unit cell equivalent circuit model for a hypothetical uniform Left-handed Transmission Line.

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current. And the quantum effect was then discussed by the mentioned results. Finally, in Section 4, we provide the summary and conclusion by making use of the result obtained in previous sections.

II. QUANTIZATION OF THE UNIT CELL EQUIVALENT CIRCUIT MODEL FOR LH TL

The fundamental characteristics of the LH TL of Fig 1.(a) are straightforwardly derived by elementary TL theory. It consists of loss-less per-unit equivalent circuit models (Fig 1.(b)) of the series-C/shunt-L prototype associated with NRI. The per-unit-length inductance L_l (H$\cdot$ m) and capacitance C_l (F$\cdot$ m) are $L_l = L_l' \cdot \Delta_z$ and $C_l = C_l' \cdot \Delta_z$, respectively. So we have the impedances $Z = 1/i\omega C_l$ (Ω/m) and admittances $Y = 1/i\omega L_l$ (S/m). According to the Fig.1(b), the complex propagation constant γ , the propagation constant β, the characteristic impedance Z_l, the phase velocity v_p, and the group velocity v_g of the unit cell equivalent circuit model for LH TL are given by[30]

$$\begin{aligned}
\gamma &= i\beta = \sqrt{ZY} = \frac{1}{i\omega\sqrt{C_l L_l}} = -i\frac{1}{\omega\sqrt{C_l L_l}}, \\
\beta &= -\frac{1}{\omega\sqrt{C_l L_l}} < 0, \\
Z_l &= \sqrt{\frac{L_l}{C_l}}, \\
v_p &= \frac{\omega}{\beta} = -\omega^2\sqrt{C_l L_l} < 0, \\
v_g &= (\frac{\partial\beta}{\partial\omega})^{-1} = \omega^2\sqrt{C_l L_l} > 0,
\end{aligned} \tag{1}$$

And the equivalent constitutive parameters for the unit cell equivalent circuit model in Fig.1(b) are[30]

$$\mu(\omega) = -\frac{1}{\omega^2 C_l} \tag{2}$$

$$\epsilon(\omega) = -\frac{1}{\omega^2 L_l} \tag{3}$$

According to Kirchhoff's law, the classical differential equations of motion of Fig.1(b) are

$$\begin{aligned}
\frac{du(z)}{dz} + \frac{j(z)}{i\omega C_l} &= 0 \\
\frac{dj(z)}{dz} + \frac{u(z)}{i\omega L_l} &= 0
\end{aligned}$$

where u and j are the position-dependent voltage and currents $u = u(z)$ and $j = j(z)$ along the line, respectively. Then their corresponding second order partial differential equations are obtained as follows,

$$\frac{d^2u(z)}{dz^2} = \frac{1}{-\omega^2 C_l L_l}u(z) = -\gamma^2 u(z) \tag{4}$$

$$\frac{d^2j(z)}{dz^2} = \frac{1}{-\omega^2 C_l L_l}j(z) = -\gamma^2 j(z) \tag{5}$$

where γ is the complex propagation constant. And the walking-wave solutions to Eq(4) and Eq(5) reaches as

$$\begin{aligned}
u(z) &= A\exp(-i\gamma z) + A^*\exp(i\gamma z) \\
j(z) &= B\exp(-i\gamma z) + B^*\exp(i\gamma z)
\end{aligned}$$

in which A^* (B^*) are the conjugate complexes of A (B). In order to exploit quantum effects of mesoscopic LH TL equivalent circuit model, we adopt the quantization method similar to Louisell [31]. In the given unit-length, i.e.,$z_0 = m\lambda$ of Fig.1(b), the Hamiltonian can be written via the characteristic impedance relation,

$$\begin{aligned}
H &= \frac{1}{2}\int_0^{z_0}(L_l j^2(z) + C_l u^2(z))dz \\
&= \int_0^{z_0} L_l j^2(z)dz \\
&= 2L_l A^* A z_0
\end{aligned}$$

where

$$\begin{aligned}
A &= a\sqrt{\frac{\hbar\omega}{2L_l z_0}}, \\
A^* &= a^*\sqrt{\frac{\hbar\omega}{2L_l z_0}}.
\end{aligned}$$

Assume that the following equation was established with the energy units $\hbar\omega$. According to the canonical quantization principle, we can quantize the system by operators $\hat{q}$ and $\hat{p}$, which satisfy the commutation relation $[\hat{q},\hat{p}]=$ i$\hbar$. Then we can define the annihilation and creation operator $\hat{a}$ and $\hat{a}^+$ by the relations

$$\begin{aligned}
\hat{a} &= \frac{1}{\sqrt{2\hbar\omega}}(\omega\hat{q} + i\hat{p}), \\
\hat{a}^\dagger &= \frac{1}{\sqrt{2\hbar\omega}}(\omega\hat{q} - i\hat{p})
\end{aligned}$$

Thus the quantum Hamiltonian of Fig.1(b) can be rewritten as

$$\hat{H} = \hbar\omega\hat{a}^\dagger\hat{a} = \frac{1}{2}(\omega^2\hat{q}^2 + \hat{p}^2)$$

which is as a quantum harmonic oscillator by imposing the quantizing condition $[\hat{q},\hat{p}]=$ i$\hbar$. Where the variables $\hat{q}$ stand for the electric charges instead of the conventional "coordinates", while their conjugation variables $\hat{p}$ represent the electric currents instead of the conventional "momenta". Thus the current in the ideal non-dissipative unit cell equivalent circuit model for the LH TL can be quantized as

$$\hat{j}(z) = \sqrt{\frac{\hbar}{4\pi m L_l^2 C_l}}[\hat{a}\exp(\frac{i}{\omega\sqrt{C_l L_l}}z) + \hat{a}^\dagger\exp(-\frac{i}{\omega\sqrt{C_l L_l}}z)] \tag{6}$$

In the similar way, the quantum voltage operator of unit cell equivalent circuit model for this LH TL can be

obtained as,

$$\hat{u}(z)=\sqrt{\frac{\hbar}{4\pi mL_lC_l^2}}[\hat{a}\exp(\frac{i}{\omega\sqrt{C_lL_l}}z)+\hat{a}^\dagger\exp(-\frac{i}{\omega\sqrt{C_lL_l}}z)] \tag{7}$$

III. THE DEPENDENCE OF NRI ON QUANTUM FLUCTUATIONS IN THERMAL FOCK SPACE

The thermal noise shouldn't be ignore when the LH TL operates at some temperature. In the following we exploit NRI dependent of the quantum fluctuations. As for the equilibrium situation, the so-called thermo field dynamics (TFD) extends the usual quantum field theory to the one at finite temperature[32]. In TFD, the tilde space accompanying with the Hilbert space, and the states and operators in the Hilbert space will find the corresponding objects in the tilde space. In this direct product space the degrees of freedom are double as the Hilbert space. The thermal degrees of freedom are introduced by doubling the degrees of freedom through tilde conjugation, and the tilde operators commute with the non-tilde operators in the tilde space[33]. Thus the creation and annihilation operators $\hat{a}^\dagger$, $\hat{a}$ associate with their tilde operators $\tilde{\hat{a}}^\dagger$, $\tilde{\hat{a}}$ according the rules:

$$[\tilde{\hat{a}},\tilde{\hat{a}}^\dagger]=1, \tag{8}$$

$$[\tilde{\hat{a}},\hat{a}]=[\tilde{\hat{a}},\hat{a}^\dagger]=[\hat{a},\tilde{\hat{a}}^\dagger]=0 \tag{9}$$

The number operators in the Hilbert space and tilde space are read as,

$$\hat{n}=\hat{a}^\dagger\hat{a},$$
$$\tilde{\hat{n}}=\tilde{\hat{a}}^\dagger\tilde{\hat{a}},$$

In the direct product space the thermal Fock state at finite temperature can be built by the thermal Bogoliubov transformation[33] through the Fock state $|\hat{n}\tilde{\hat{n}}\rangle=|\hat{n}\rangle\otimes|\tilde{\hat{n}}\rangle$ at zero temperature:

$$|\hat{n}\tilde{\hat{n}}\rangle_T=\hat{T}(\beta)|\hat{n}\tilde{\hat{n}}\rangle$$

where $\hat{T}(\beta)$ is a thermal unitary operator which is defined as

$$\hat{T}(\beta)=exp[-\beta(\hat{a}\tilde{\hat{a}}-\hat{a}^\dagger\tilde{\hat{a}}^\dagger)] \tag{10}$$

the parameter β is the thermal unitary operator relating the thermal photos n_0 in the thermal vacuum state: $sinh\beta=n_0$. The thermal photos n_0 and temperature T are ruled by the Boltzmann distribution

$$n_0=[exp(\hbar\omega/k_BT)-1]^{-1} \tag{11}$$

in which ω, k_B are the angular frequency of light field and the Boltzmann constant, respectively. The bosonic operators in TFD can relate each other by the thermal Bogoliubov transformation as following,

$$\hat{T}^\dagger(\beta)\hat{a}\hat{T}(\beta)=\mu\hat{a}+\tau\tilde{\hat{a}}^\dagger, \tag{12}$$

$$\hat{T}^\dagger(\beta)\hat{a}^\dagger\hat{T}(\beta)=\mu\hat{a}^\dagger+\tau\tilde{\hat{a}} \tag{13}$$

where μ=$cosh\beta$, τ=$sinh\beta$. Then from Eqs.(12) and (13), the average value of the current and the voltage in thermal Fock state can be calculated as,

$$\begin{aligned}
\overline{\hat{j}(z)}&={}_T\langle\hat{n}\tilde{\hat{n}}|\hat{j}(z)|\hat{n}\tilde{\hat{n}}\rangle_T\\
&=\sqrt{\frac{\hbar}{4\pi mL_l^2C_l}}\,{}_T\langle\hat{n}\tilde{\hat{n}}|\hat{a}|\hat{n}\tilde{\hat{n}}\rangle_T\exp(\frac{i}{\omega\sqrt{C_lL_l}}z)\\
&+{}_T\langle\hat{n}\tilde{\hat{n}}|\hat{a}^\dagger|\hat{n}\tilde{\hat{n}}\rangle_T\exp(\frac{-i}{\omega\sqrt{C_lL_l}}z)\\
&=\sqrt{\frac{\hbar}{4\pi mL_l^2C_l}}\langle\hat{n}\tilde{\hat{n}}|\hat{T}^\dagger(\beta)\hat{a}|\hat{n}\tilde{\hat{n}}\rangle_T\exp(\frac{i}{\omega\sqrt{C_lL_l}}z)\\
&+{}_T\langle\hat{n}\tilde{\hat{n}}|\hat{a}^\dagger\hat{T}(\beta)|\hat{n}\tilde{\hat{n}}\rangle\exp(\frac{-i}{\omega\sqrt{C_lL_l}}z)\\
&=0,
\end{aligned} \tag{14}$$

$$\overline{\hat{u}(z)}={}_T\langle\hat{n}\tilde{\hat{n}}|\hat{u}(z)|\hat{n}\tilde{\hat{n}}\rangle_T=0, \tag{15}$$

Then the quantum fluctuation of the current in the unit cell equivalent circuit model is

$$\begin{aligned}
\overline{(\Delta\hat{j})^2}&=\overline{\hat{j}(z)^2}-\overline{\hat{j}(z)}^2\\
&=\overline{\hat{j}(z)^2}\\
&={}_T\langle\hat{n}\tilde{\hat{n}}|\hat{j}(z)^2|\hat{n}\tilde{\hat{n}}\rangle_T\\
&=\frac{\hbar}{4\pi mL_l^2C_l}\langle\hat{n}\tilde{\hat{n}}|\hat{T}^\dagger(\beta)[\hat{a}^2\exp(\frac{2i}{\omega\sqrt{C_lL_l}}z)+\\
&\hat{a^\dagger}^2\exp(\frac{-2i}{\omega\sqrt{C_lL_l}}z)+\hat{a}\hat{a}^\dagger+\hat{a}^\dagger\hat{a}]\hat{T}(\beta)|\hat{n}\tilde{\hat{n}}\rangle\\
&=\frac{\hbar}{4\pi mL_l^2C_l}[\langle\hat{n}\tilde{\hat{n}}|\hat{T}^\dagger(\beta)\hat{a}^2\hat{T}(\beta)|\hat{n}\tilde{\hat{n}}\rangle\exp(\frac{2i}{\omega\sqrt{C_lL_l}}z)\\
&+\langle\hat{n}\tilde{\hat{n}}|\hat{T}^\dagger(\beta)\hat{a^\dagger}^2\hat{T}(\beta)|\hat{n}\tilde{\hat{n}}\rangle\exp(\frac{-2i}{\omega\sqrt{C_lL_l}}z)\\
&+\langle\hat{n}\tilde{\hat{n}}|\hat{T}^\dagger(\beta)\hat{a}\hat{a}^\dagger\hat{T}(\beta)|\hat{n}\tilde{\hat{n}}\rangle+\langle\hat{n}\tilde{\hat{n}}|\hat{T}^\dagger(\beta)\hat{a}^\dagger\hat{a}\hat{T}(\beta)|\hat{n}\tilde{\hat{n}}\rangle]\\
&=\frac{\hbar}{4\pi mL_l^2C_l}(\mu^2+\tau^2)(1+2n)\\
&=\frac{\hbar}{4\pi mL_l^2C_l}(1+2n_0)(1+2n)
\end{aligned} \tag{16}$$

In the similar way, the quantum fluctuation of the voltage in the unit cell equivalent circuit model for LH TL is calculated as

$$\overline{(\Delta\hat{u})^2}=\frac{\hbar}{4\pi mL_lC_l^2}(1+2n_0)(1+2n) \tag{17}$$

Substituting Eq.(11) into Eq.(16) we can obtain

$$\begin{aligned} 1+2n_0 &= \frac{\exp\left(\frac{\hbar\omega}{2k_BT}\right)+\exp\left(-\frac{\hbar\omega}{2k_BT}\right)}{\exp\left(\frac{\hbar\omega}{2k_BT}\right)-\exp\left(-\frac{\hbar\omega}{2k_BT}\right)} \\ &= coth\left(\frac{\hbar\omega}{2k_BT}\right) \end{aligned} \tag{18}$$

Then combining the characteristic parameters of the unit cell equivalent circuit model for LH TL in express (1) $\sim$ (3), Eq.(16) and Eq.(18), its constitutive parameter, i.e., the refractive index can be written as follows,

$$n_r = -\frac{2z_0 Z_l \overline{(\Delta\hat{j})^2}}{\hbar\omega^3(1+2n)coth(\frac{\hbar\omega}{2k_BT})} \tag{19}$$

IV. RESULTS AND DISCUSSION

According Eq.(19), the refractive index of the unit cell equivalent circuit model for LH TL is dependent of the temperature, frequency, the number of photos, the characteristic impedance, the unit-length of the unit cell equivalent circuit model and the quantum fluctuation of the current. To understand these dependence intuitively, we plot the refractive index of the unit-length equivalent circuit model for LH TL dependent of the thermal number of photons in Fig.2, dependent of the diverse temperatures in Fig.3 and dependent of the frequencies in Fig.4 .

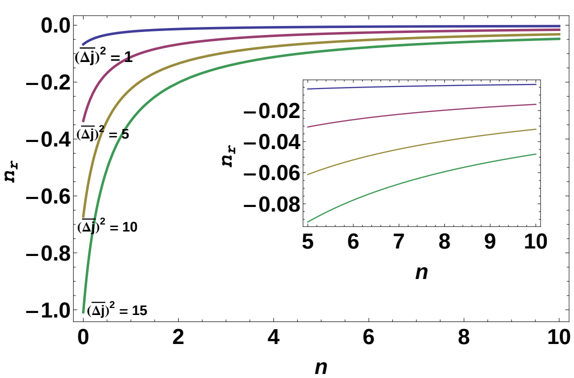

FIG. 2. Dependence of the refractive index n_r and the thermal number of photons n under different quantum fluctuation of the current in the unit-length equivalent circuit model for LH TL.

The quantum fluctuation is the significant character of the mesoscopic hypothetical uniform LH TL, and the quantum fluctuation may play an important role in the refractive index. Fig.2 shows the dependence of the refractive index n_r and the thermal number of photons n under different quantum fluctuation of the current with the condition of $Z_l = 1\Omega/m$, $\omega = 2\pi f, f = 100GHz$, $T = 273K$. It reveals the quantum fluctuation of the current puts a positive impact on the NRI. The increasing fluctuation of the current incurs the increasing NRI values. The curves in Fig.2 also display the NRI decreases with the increasing thermal photons at the low light level. However, The inset part in Fig.2 demonstrates that the increasing fluctuation of the current influences the NRI triflingly when the thermal photons $n > 5$.

We must examine the temperature T influences on the NRI of the mesoscopic unit-length equivalent circuit model for LH TL. If we replace circuit components in the unit-length equivalent circuit model for LH TL, the characteristic impedance can be set $Z_l = 50\Omega/m$ with the current fluctuation $\overline{(\Delta\hat{j})^2} = 5$ in Fig.3 .

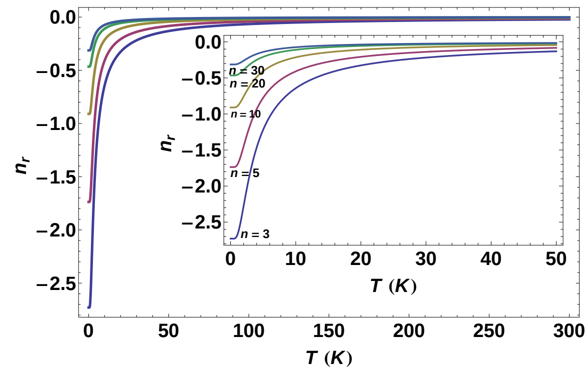

FIG. 3. Dependence of the refractive index n_r and the temperature T under different thermal photons in the unit-length equivalent circuit model for LH TL.

Fig.3 shows the destructive dependence of the temperature T and the refractive index n_r when the thermal photons vary from the low level to the moderate level. It demonstrates the mesoscopic ideal LH TL equivalent circuit operates well at low temperature T with low level thermal photons.

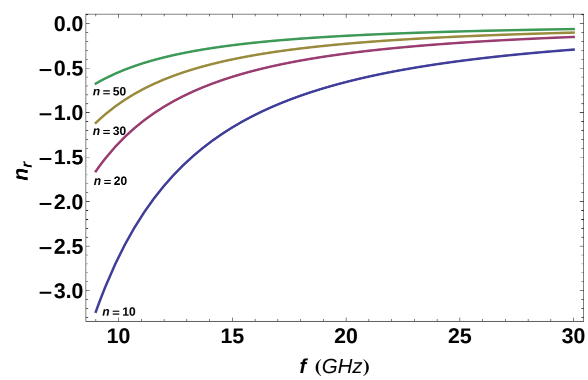

FIG. 4. Dependence of the refractive index n_r and the frequency f under different thermal photons in the unit-length equivalent circuit model for LH TL.

Another important parameter is the operation frequency of the mesoscopic ideal LH TL equivalent circuit. Fig.4 shows NRI of the mesoscopic ideal LH TL when it operates within the microwave frequency band [34] with $\overline{(\Delta\hat{j})^2}$=18, $T = 300K$ and $Z_l = 50\Omega/m$. When the meso-

scopic ideal LH TL equivalent circuit operates at low frequency region, the NRI changes in a large range, and the conclusion rules the course of thermal photons increasing within the moderate magnitude. It demonstrates the TL show NRI when the LH TL operates at a lower frequency which coincides with the macroscopic LH TL[34].

V. CONCLUSION

We have proposed a quantization scheme for an ideal loss-less mesoscopic LH TL circuit, and analysed the thermal fluctuations of current and the voltage in thermal Fock by the TFD theory. With the thermal fluctuation of current we discussed the NRI for the LH TL circuit. At some temperature, the NRI is linear dependent of the thermal fluctuation of current and destructive dependent of the frequency and the thermal photons within the microwave frequency band. However, the NRI is decreasing along with the temperature arises. Operating at a lower frequency, temperature and little thermal photons, the ideal loss-less mesoscopic LH TL equivalent circuit is convenient to has NRI, which coincides with the macroscopic LH TL.

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